A Detailed Examination of an X-line Region in the Distant Tail: Observations of Jet Flow, B_z Reversals and a Pair of Slow Shocks

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To be submitted to Geophysical Research Letters

April 15, 1994

Abstract: We report for first time an observations of magnetic reconnection at a distant neutral line at about x= -230R_e. The neutral line has an earthward motion. A full set of signatures of the magnetic merging process has been seen at this region. These features include a reversal of plasma flows from earthward to tailward, a pair of slow shocks and the magnetic field X-type line. The spacecraft first enters the earthward plasmasheet traversing a slow shock from the south lobe, An earthward plasma flow of about 500km/s with a embedded positive B_z is detected and then reversals of both the magnetic B_z sign and plasma flows indicate a crossing of the neutral line. The spacecraft enters a region of tailward plasma flow with a speed of about 600km/s and a negative B_z, indicating entry into the downstream plasmasheet. Subsequently, the spacecraft returns into the south tail lobe across another slow shock again. The coplanary analyses show that the two slow shocks have consistent orientations and plasma merging speeds with that predicted by the Petschek's model. However, during this time a southward IMF and near-earth geomagnetic activity did not be seen. Thus it suggests that this reconnection process occured locally. The magnetic merging probably is caused by the magnetic stresses built-up in the. distant tail.

INTRODUCTION

Since Dungey [1961] suggested theoretically that the interaction of the solar wind with the magnetosphere may occur through a magnetic reconnection process, subsequent observation quickly confirmed his speculations. Central to this model is an X-type neutral line in the magnetopause and in the geomagnetic tail. Through magnetic merging, a X-type topologic line is formed. On the both sides, the magnetic field lines are cut and merged. Through this process, the magnetic energies are converted into the plasma thermal and kinetic energies. Thus, we expect to see the jet-like. plasma flows from the merging region. However, full signatures of the X-line topology and jetting have never been clearly observed. Thus, some doubts to the realities of the reconnection model have arisen, even though people have argued that the. reconnection Process is so transient in time and so limited in spatial scale, that the process may easily escape our measurements.

Dayside reconnection between the IMF and the magnetosphere will add the field lines to the tail. Consequential nightside reconnection in the tail will return these field lines to the forward magnetosphere. Some simplified theories of this process have predicted the formation of four slow mode shocks which bound a field reversal layer and are connected together at the neutral line in the geomagnetic tail [Petschek, 1964; Vasyliunas, 19-/5; Sonnerup, 1979]. The existence of these slow shocks in the near-earth tail and the distant tail ($x < -200 R_e$) have been confirmed by ISEE observations [Feldman et al., 1984 slid 1987; Smith et al., 1984]. The passages of the plasmoids associated with near-earth substorm activity have been observed from the near earth tail (about -?()]{C) to the far tail between -80 and -140 R_e [Baker et al., 1984]. During the passage of a plasmoid, we see clearly a magnetic field directional transition from south to north (e.g., B_z reversal), associated with strong tailward plasma flows [Hones et al., 1984]. Previously Scholer et al. [1986] have shown an example of reconnection-like phenomena at $140 R_e$. However, in their event the negative B_z are extremely transient (less than ? rein), and no slow shock was identified. The correlation between the positive B_z and the earthward electron plasma flow is not obvious.

Through a careful examination of 1S1 :I:-3 data during the distant tail passes, we have found an eve nt that clearly shows magnetic merging taking place in the distant tail. As we will illustrate, both earthward and tailward plasma flows on both sides of a neutral line of the magnetic field reversal are found. We also see a pair of slow shocks bounding the plasmasheet. We believe this is the most well documented case at magnetic merging in the geomagnetic tail to date.

INSTRUMENTATION

The data for this study was generated during ISEE-3 second distant tail pass. ISEE-3 traversed the distant geomagnetic tail at around x(GSM) = -220R_e between June 23 and July 22, 1983. The magnetic field measurements were obtained by the Jet f'repulsion 1 aboratory magnetometer [Frandsen et al., 1978]. In high resolution data rate, this instrument measured 6 vectors per second. For this study we make use of 30-sec averages of the field.

The plasma observations presented here were obtained by the 1 os Alamos electron analyzer [Bame et al., 19831. Two-dimensional electron data are integrated over ±67.5° polar- angle intervals centered on the spacecraft spin plane, which is nearly coincident with the ecliptic. Although a complete spectrum was measured in 3s, the next measurements were, most often separated in time by ~ 84s. At times, this separation was reduced to 1?s. The electron data we used in this study include el e ct ron density N_e, temperature T_e and two-dimensional plasma flow velocity V (V_x, V_y). The ion data were not available during the distant tail pass.

OBSERVATIONS

Even though the tailward plasma flow generally dominates the entire distant plasmasheet, We have found four cases of the earthward plasma flows associated with slow shocks. Two cases display the neutral line crossings [Ho et al., 1994]. Figure 1 gives an example of the spacecraft passing through a neutral line in the distant tail. During July 8, 1983, ISEE-3 was in the second distant tail excursion. The spacecraft had a GSE location X=-235.5, Y=10.8, Z=-8.5R_e and a GSM location X= -235.5, Y= 7.6, Z= -11.4R_e. The spacecraft had a relative motion from the south tail lobe into the plasmasheet and then returned back to the south lobe. We will use a GSE coordinate system to describe this process, including the components of the plasma velocity and the magnetic field in this study.

In Figure 1 from top to bottom in order are the electron density N_e, electron temperature T_e, plasma bulk velocity V_x, V_y, and total plasma velocity V with 12 sec resolution. Next are the three magnetic field components, B_x, B_y, B_z and the total magnetic field strength B. 30 sec averages of the field data were constructed for the shock study (to reduce high frequency fluctuations).

Between 11:00 UT and 12:20 UT, ISEE-3 was completely inside the south tail lobe.. We see a lower N_e of about 0.2cm^{-3}, lower T_e of about 0.8×10^5K, and also a lower tailward plasma velocity ($V_x \sim -200$km/s, $V_y \sim 0$). The magnetic field is strong ~12nT and mainly with a B_x component (~ -11.5nT), indicative of the lobe fields. At 12:20 the spacecraft partially entered the plasmasheet (or plasmasheet boundary layer). Thus we see an increase in the N_e and T_e parameters and fluctuations in V_x and V. The magnetic field has a decrease of 2 ~4 nT. However, the spacecraft did not completely enter the plasmasheet. Instead, it oscillated between the plasma sheet and the boundary layer. As shown in the plot, at 12:38UT, ISEE-3 entered the lobe and at 2:47 JT entered he plasmasheet boundary layer once again. At 12:55UT it first crossed the slow shock to completely enter the plasmasheet. The magnetic field suddenly drops from 10 nT to 3 nT and N_e increases from 0.11 to 0.22 cm^{-3}. The temperature T_e jumps from 0.7×10^6 to 2.2×10^6K. The velocity V_x changes from a tailward direction into a earthward one (+400km/s). The magnetic field B_x component becomes near zero. B_z has a significant positive component of +2.5 nT. It indicates that ISEE-3 was in the plasmasheet of the earthward side of the magnetic merging egion. These features only last until 13:17UT (or 3:20UT because of a data gap). Then T_e suddenly drops to 0.7×10^6K and N_e also slightly drops. The V_x reverses direction from earthward into tailward. Roughly in the same time, the magnetic field B_z component reverses direction from positive into a negative sign, while B_x does not have any obvious change. This can be interpreted as a crossing of an X-type neutral line. We have used a vertical line to mark this transition time. ISEE-3 entered the tailward side plasmasheet at 13:22UT. We see a higher N_e and T_e again. V_x is large and in a tailward direction with a value around -600 ~ -700 km/s, while the B_x eaches -1.9 nT. After 13:53UT S E-3 crossed another slow shock and eturned to the south lobe. All parameters of T_e, N_e, V, and B eturn to approximately the previous values at 12:00UT.

For most observations of slow shocks in the distant ail, the slow shocks and the plasmasheet are generally crossed vertically along the z direction from the north to the south or vice versa (due to north-south flapping). Thus it is very difficult to clearly note a neutral line and bi-direction jet plasma flow from the reconnection region. However, the event illustrated here quite possibly has a relatively horizontal crossing. The spacecraft crossed the neutral line from one side of the plasmasheet to the other. crossed a slow shock on one side of the X-line and exited on the other side. In order to confirm above analyses, we have used coplanarity theorem and Rankine-Hugoniot relations to examine the. two slow shocks,

Interpretations

We use the coplanarity relation to calculate the shock normal for the two plasmasheet boundary crossings. All measured parameters are listed in Table 1. They include the upstream magnetic field B_u, downstream field B_d, and N_e, T_e, V_x, V_y and V for both upstream and down stream. After the "entry" shock there are a positive B_z component and a positive V_x downstream plasma flow. Prior to the "exit" shock the.rc are a negative B_z component and a negative downstream flow. In our reference system, we mean "upstream" to be the tail lobe, while "downstream" is the plasmasheet, no matter which one is crossed first.

When we rotate the both upstream and downstream magnetic fields into a shock normal coordinate system, for the entry (first) shock, we obtain a shock normal vector $\hat{n}_1$ (-0.128, 0.562, -0.817). The n_z is anti-parallel to the z direction in a GSE coordinate system. Thus we have a negative B normal component (B_n = -0.9± 0.3 nT) for a positive B_z component. The maximum errors in the observations come from the standard deviation of both upstream and downstream field values in Figure 2. For the exit (second) shock, we obtain another shock normal of $\hat{n}_2$(-0.225, 0.193, 0.955). Its n_z has a positive projection in the z axis, However, because B_z is anti-parallel to the z direction, we still obtain a negative B_n (-1.1±0.4nT) as shown in Figure 3.

In order to describe these two shock as clearly as possible, we need to define some angles using the magnetic field geometry relation. When we use Petschek's simplified slow shock model as shown in Figure 4, we need to project the magnetic field and the shock normal into the x-z plane. The first angle is θ_{nz} which is the angle between the normal n and the z axis. $\theta_{nz} = \cos^{-1} n_z$. The second angle is ξ which is the angel between the shock normal in the x-z plane and the z axis. Thus $\xi = \tan^{-1} n_x/n_z$. If n_y is equal to 0, then $\theta_{nz} = \xi$. The third angle is η which is the angle between the shod normal n in the x-z plane and the field B in the x-z plane. If both n_y and B_y are equal to 0, then $\eta = \theta_{Bn}$, where $\eta = \cos^{-1} \vec{B}_{xz} \cdot \vec{n}_{xz} / |\vec{B}_{xz}||\vec{n}_{xz}|$. The fourth angle χ is between the magnetic field line in the x-z plane and the x axis. The angle χ is the acute angle of (η - ξ). These angles are also listed in 'Table 1 respectively.

Through a detailed analysis of the shock normal orientation, we can find that the two shocks have different orientations. In an x-z Cartesian coordinate system (same as x-z of GSE), the first (entry) shock has a normal orientation consistent with the spacecraft crossings from left-top quadrant to right-bottom quadrant. It has an angle ξ_1 of 18.5° as shown in Figure 4. So the shock surface should have an orientation from left-bottom to right-top quadrants. Based on the magnetic field orientation, we determine that this shock is the one of the left-bottom side in Figure 4, because magnetometer observed a positive B_z field after entering the plasmasheet from the south lobe.

The second (exit) shock is consistent with the spacecraft going from left-top to right-bottom quadrants of Figure 4,. The shock normal points to right-top quadrant with minus n_x and plus n_z. Thus we identify this shock with the right-bottom side of Figure 4. The angle ξ_2 between the shock surface and the x axis is 1 '2.'/". There is a slightly asymmetry for both the entry shock and the exit shock, because there is little difference in the ξ angles. This difference is probably within the errors of the measurements.

We next use Rankine-Hugoniot relations to calculate the plasma flow velocity along the normal direction in the upstream region. All calculated speeds also are shown in Table 1, which include the Alfven speed V_A, the Alfven speed in the normal direction V_{An}, the plasma flow velocity along the normal V_n and the sound speed C_s. Here we have assumed a 30 eV upstream ion temperature [T. Mukai, private communication, 1994] because of absence of ion data. We find the plasma flow velocities along the normal V_n are greater than C_s and less than V_{An}. Thus the two shocks satisfy the slow mode shock condition and have the structures as proposed by Petschek [1964].

In the simple model of the tail magnetic field reconnection proposed by Petschek [1964], slow mode shocks are important interfaces where magnetic energy from the magnetic lobe is converted into plasma kinetic or thermal energy in the plasmasheet. Using the model in Figure 4, the magnetic merging rate may be calculated. Based on conservation of B_n and the tangential components of electric field in a steady state, together with the frozen-in condition, we have the tangential plasma speed [Hill, 1975]:

$$V_{xd} = V_{Au} \cos\chi = V_{Au} \sin(\eta - \xi) \qquad (1)$$

Using on the Alfven velocities V_{Au} listed in Table 1, we obtain that the outgoing plasma flow speeds V_{xd} downstream of the shock. They are + 636km/s for the entry shock side plasmasheet, and -653km/s for the exit shock side plasmasheet, respectively. The speeds are basically consistent with the speeds V_x we observed in the downstream. But the observed V_x in the earthward side plasmasheet has slightly lower values than the calculated one.

We also may Calculate the merging speeds (the plasma inflow speed toward the x-y plane neutral sheet). The speeds have the following expression as a function of upstream parameters and of the density jump [Hill, 1975]:

$$V_{zu} = V_{Au} \sin\chi / (1 + N_u / N_d) = V_{Au} \cos(\eta - \xi) / (1 + N_u / N_d) \quad (2)$$

Using the average jump ratios of density across the shocks, we have upstream merging speed V_{zu} of 253km/s for the entry shock, and 272km/s for the exit shock. Considering the θ_{nz} angles, the two inflow speeds may be slightly reduced, but still large.r than the upstream normal flow speeds V_{nu}.

DISCUSSION

When we examine the substorm relationship at the same time when the reconnection occurs in the distant tail, we find that (his is a relatively quiet period in the near-earth. Between 11:00 UT and 16:00 UT, the AE index is below 400" nT. AE index from the background of 1 ()() nT arises to nearly 400 nT around 13:0 0UT. This is a small geomagnetic activity, but dots not rule out small substorms. We have also examined the. IMF orientation (IMP-8) during the same time. '1'here. is a positive B_z component with an average about 1.6 nT between 11 :00 UT and 1 6:00 UT. Before 11 :00 UT there is a four hour interval with a negative IMF B_z - -2.9nT. It seems unlike.ly that there is a relationship between the distant tail reconnection event and a substorm three hours pr i or.

ISEE-3 plasma data analyses [Zwickl et al., 1 984] show that an earthward plasma flow in the plasmasheet is often detected. Beyond ~120 R_e the plasma bulk velocity in the plasma sheet is almost exclusively tailward. However, statistical studies of magnetic field properties [Tsurutani et al., 1 984] suggest that the distant neutral line is most probably located at - ?.()()]<$_c$ distance. Furthermore, Tsurutani et al. [1987] show that the large scale field variations with North-then-South signatures across the plasmasheet occur during all geomagnetic activity levels. Scholer et al. [1986] have shown **a** lccoll[lcctic~l)-like event at ~140Re occurred during quiet geomagnetic conditions. In a recent statistical study []1o et al., 1994] we also show that there is no obvious dependence of the occurrences of the slow shocks, plasmasheet crossings in the. distant tail on the near-earth substorm activities. Thus we suggest that these phenomena of reconnection and slow shocks we observed are a local process, and may be independent of substorm processes occurring close to earth.

SUMMARY

We first report a clearly magnetic merging signature occurring at distant tail ~ 230 R_e. The observations anti calculations are consistent with Petschek's simplified s1ow shock model. Around the same time., a southward IMF and a strong, near-earth substorm activity did not be observed. It may imply that a magnetic stress built-up in the distant tail is probably responsible to this reconnection process.

The spacecraft enters the plasmasheet from the south lobe across a slow mode shock. In the earthward plasmasheet a significant earthward plasma flow and positive B_z are detected. Then, through a relatively earthward motion of the neutral line, the spacecraft crosses the magnetic merging region. Thus reversals in the plasma flow direction and the. magnetic field B_z component are observed. After this a tailward plasmasheet with strong tailward plasma flow and negative B_z is observed. Finally, ISEE-3 crosses an exit s1ow shock and back to the south lobe again.

Acknowledgments: The author *(CM.]* 10) thanks the support from the National Research Council Associateship Program. The research conducted at the. Jet Propulsion Laboratory, California Institute of Technology was performed under contract to the National Aeronautic and Space Administration.

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Table 1. Plasma and Magnetic Field Parameters Across Two Shocks

July 8, 1993	Enter Shock	Exit Shock
Time Interval	12:14:30-13:07:00	*13:34:00-14:01:30*
$B_u (B_x, B_y, B_z)$	-9.4, 1.1, 1.4 nT	-1 0.6, 0.3, -1.2 nT
$B_d (B_x, B_y, B_z)$	-2.1, -0.3, 0.811'1'	-2.8, -0.9, -1.911'1'
B_n	-0.9± 0.3 nT	-1.1± 0.4 nT
$n (n_x, n_y, n_z)$	-0.128, 0.562, -0.817	-0.225, 0.193, 0.955
N_{eu}	0.10 cm^{-3}	0.11 cm^{-3}
N_{ed}	0.22 cm^{-3}	0.27 cm^{-3}
T_{eu}	0.7×10^6K	0.6×10^6K
T_{ed}	2.2×10^6K	1.7×10^6K
$V_u (V_x, V_y)$	149 (-147, 22)km/s	140 (-138, 20)km/s
$V_d (V_x, V_y)$	465 (439, 152)km/s	680 (668,126)km/s
θ_{Bnu}	81°± 9°	79°± 8°
θ_{Bnd}	71± 6°	51°± 9°
θ_{nz}	37°± 3°	17°± 2°
ξ	18.50:11.6°	12.7°± 1.5°
η	78°± 100	73°± 9°
V_{Au}	738 km/s	748 km/s
V_{Anu}	140 ± 15km/s	156 ± 24km/s
V_{nu}	117 ± 12km/s	131 ± 20km/s
C_{su}	108 km/s	105 km/s
M_{An}	0.93	0.91
β_e	0.04	0.04

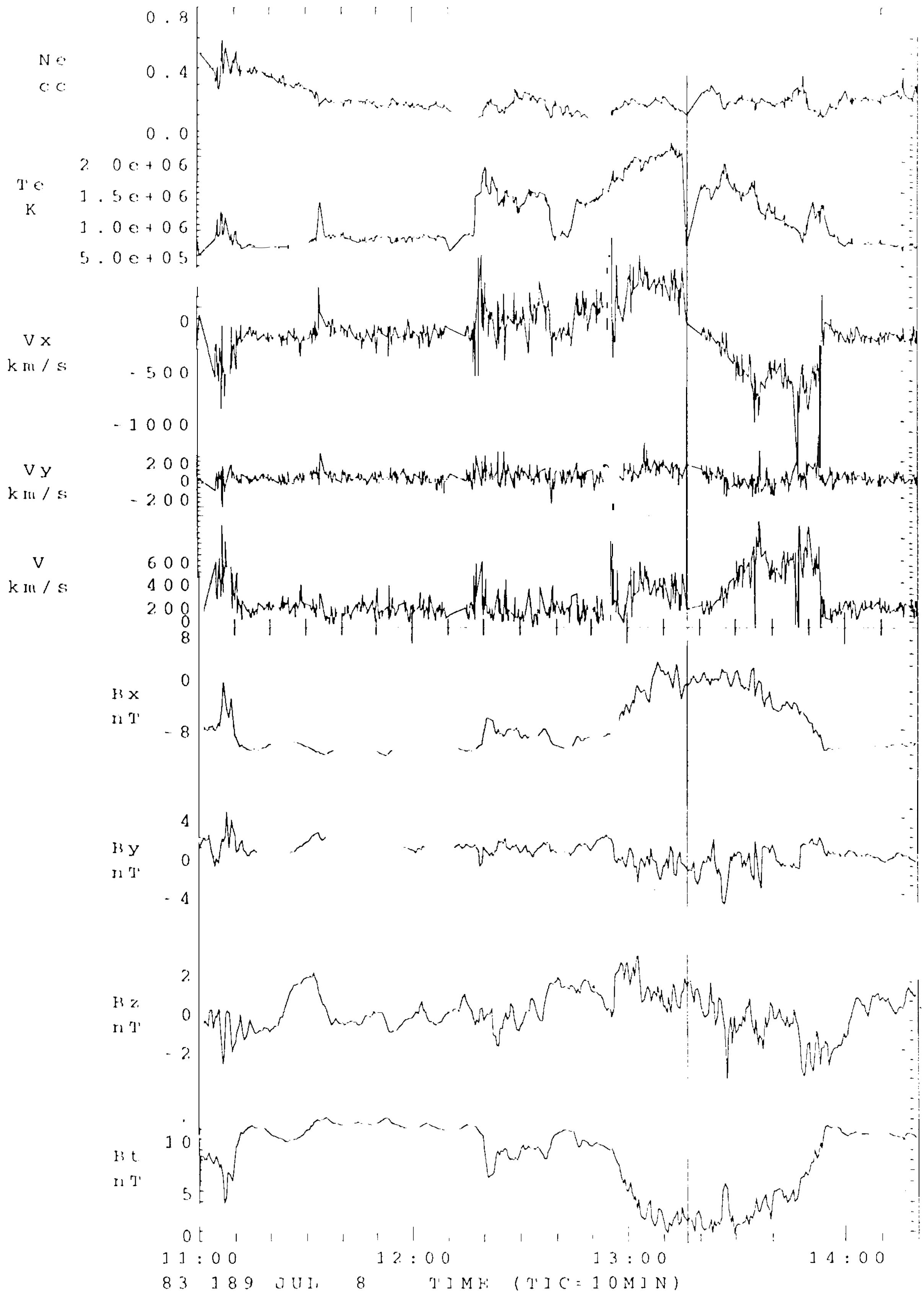
Figure Captions

Figure 1. An c.vent of crossings of the slow slinks, the jet plasma flows and the neutral line in the distant tail in July 8, 1983. From top to bottom are consequently the electron density N_e, electron temperature T_e, plasma bulk velocity x component V_x, its y component V_y, and total plasma velocity V, three magnetic field components, B_x, B_y, B_z and the total magnetic field strength B. The vertical line roughly gives the time of the neutral line crossing.

Figure 2.. The data selection of the upstream and downstream of the entry shock between 12:47 UT and 13:07 UT. Using the coplanarity relation, we have calculated the shock normal which is shown in the right side of the plot.

Figure 3. Applying of coplanary theorem to the exit slow shock occurring at 13:34 UT and 14:01 UT. The rotation metrix and the errors are shown in the right side..

Figure 4. A simplified Petschek's slow mode shock mode] which is perfectly adapted the observations. The spacecraft enters the central plasmasheet from the bottom south lobe. Then it crosses the neutral line and returns to the south lobe.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cc
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0.4
0.0
Te
K
2.0e+06
1.5e+06
1.0e+06
5.0e+05
Vx
km/s
0
-500
-1000
Vy
km/s
200
0
-200
V
km/s
600
400
200
0
Bx
nT
8
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By
nT
4
0
-4
Bz
nT
2
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10
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11:00
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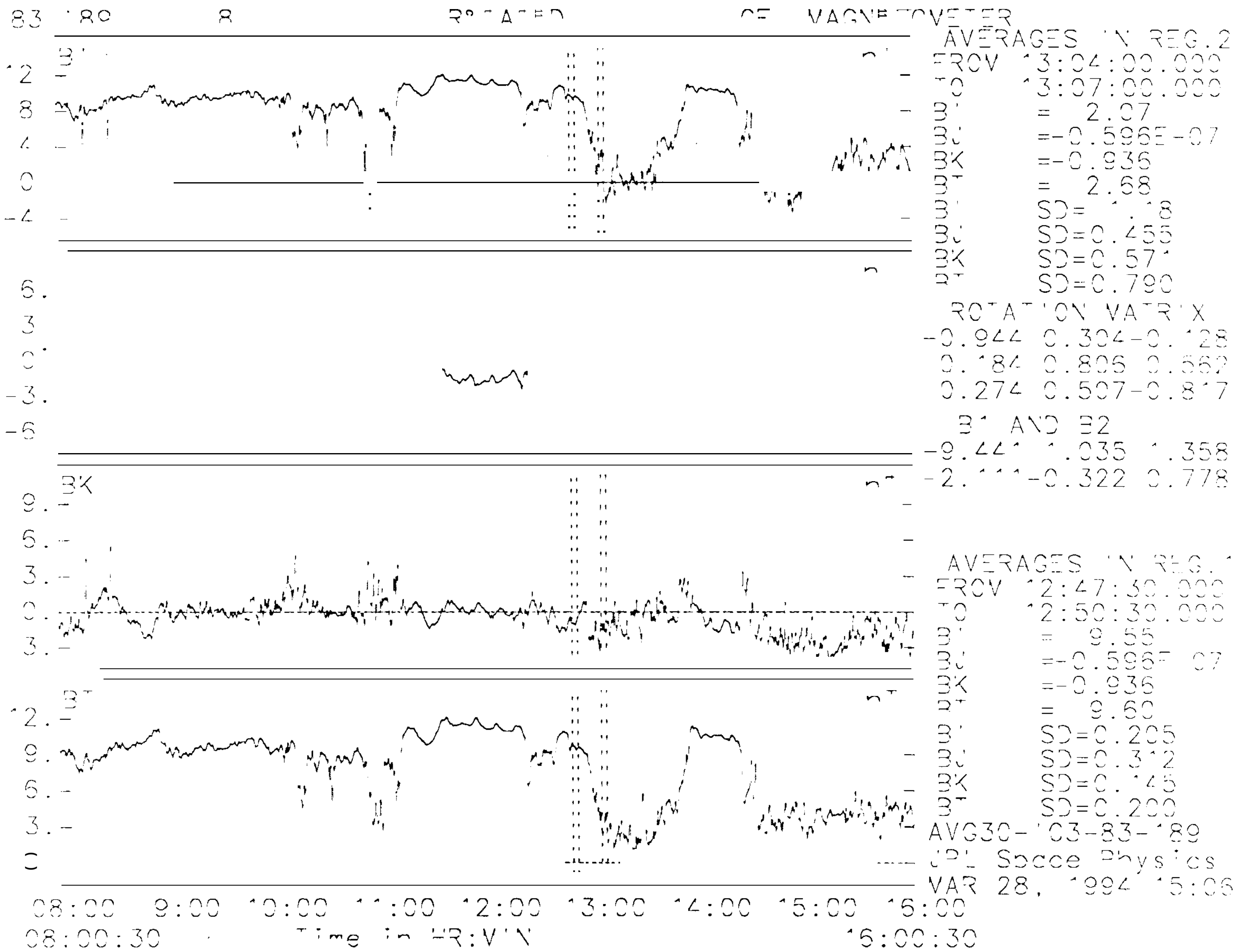
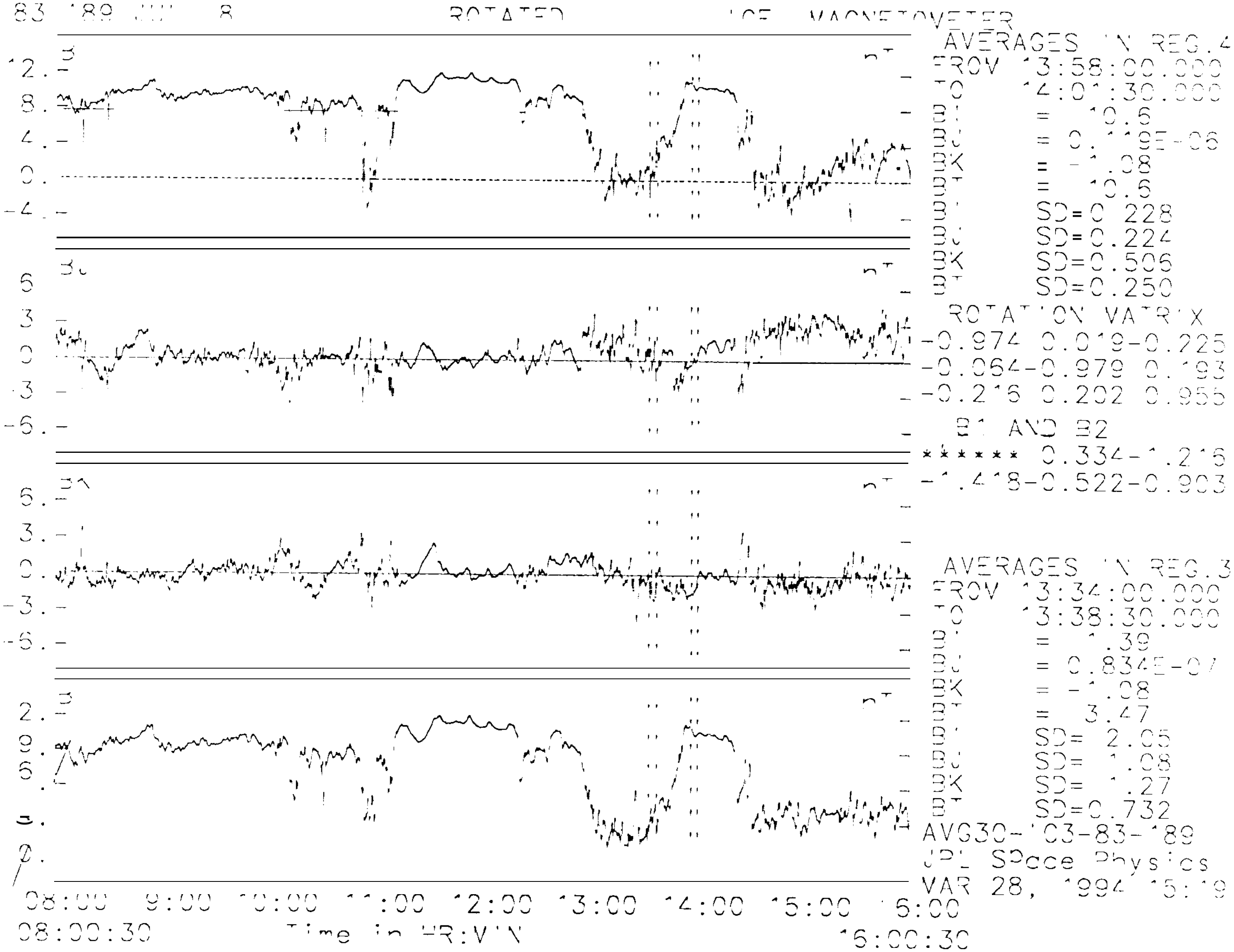
83 189 JUL 8 TIME (TIC=10MIN)

Fig 1



83 189
8
MAGNETOMETER
AVERAGES IN REG.2
FROM 13:04:00.000
13:07:00.000
= 2.07
=-0.596E-07
BK =-0.936
= 2.68
SD=0.455
BK SD=0.571
SD=0.790
ROTATION MATRIX
-0.944 0.304
0.805
0.274 0.507
B1 AND B2
1.035 1.358
-0.322 0.778
BK
AVERAGES IN REG.1
FROM 12:47:30.000
12:50:30.000
= 9.55
BK =-0.936
= 9.60
SD=0.205
BK SD=0.145
SD=0.200
AVG30-103-83-189
JPL Space Physics
MAR 28, 1994 15:06
08:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00
08:00:30 16:00:30



ROTATED
AVERAGES IN REG.4
FROM 13:58:00.000
SD=0.228
SD=0.224
SD=0.506
SD=0.250
ROTATION MATRIX
-0.974 0.019-0.225
-0.064-0.979 0.193
-0.216 0.202 0.955
B1 AND B2
****** 0.334-1.216
-1.418-0.522-0.903
AVERAGES IN REG.3
FROM 13:34:00.000
TO 13:38:30.000
= 3.47
SD= 2.05
SD= 1.08
SD= 1.27
SD=0.732
AVG30-103-83-189
JPL Space Physics
MAR 28, 1994
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08:00:30
Time in HR:MIN
16:00:30

Fig 3

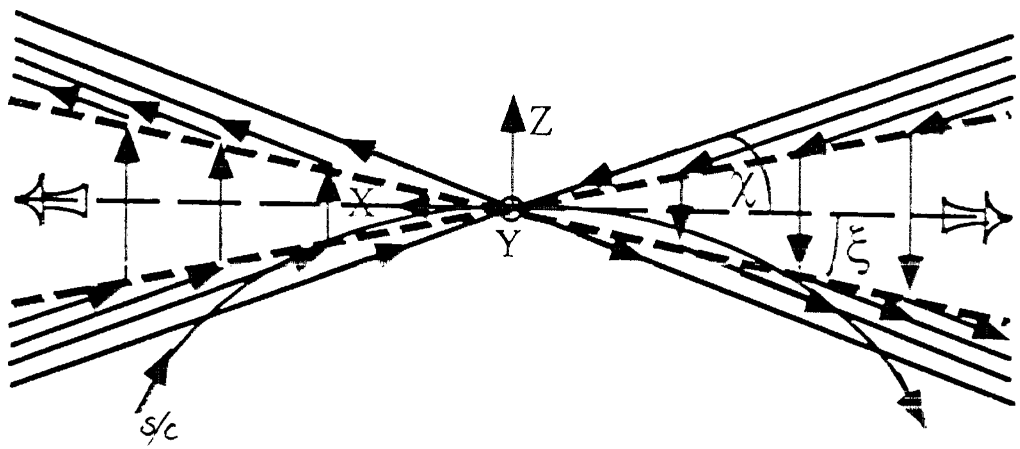

Fig 4